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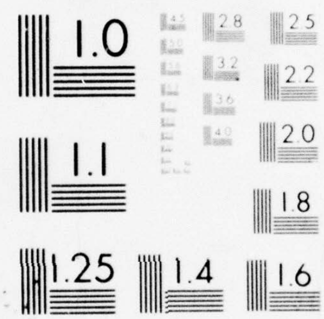
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RADC-TR-76-257
Final Technical Report
August 1976

KLYSTRON-TWT HYBRID EFFICIENCY IMPROVEMENT

Varian Associates

ROME AIR DEVELOPMENT CENTER
AIR FORCE SYSTEMS COMMAND
GRIFFISS AIR FORCE BASE, NEW YORK 13441

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Intense-Interaction Cloverleaf Structure
Higher Order Mode Loading

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

This final report covers effort from 16 December 1974 through 30 June 1976. The effort was expended as Phase II of a theoretical and experimental investigation of methods of improving the conversion efficiency of relatively broadband linear beam amplifiers operating at approximately 1 MW of peak power.

The Phase I "short-stack" intense-interaction cloverleaf structure design was modified. Extensive cold testing was performed with an emphasis on selective

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loading of the higher-order modes that supported oscillations in the Phase I tube. Computer-aided calculations predicted 43% minimum efficiency over a 10% bandwidth with a midband efficiency of 56%.

Performance was limited by an efficiency dip near the low end of the band, a gain hole in band, an rf drive-induced oscillation near saturation at some combinations of beam voltage and current, and a beam deduced to be of smaller diameter than was assumed in the calculations.

Under the above conditions the best saturation performance was 42% midband efficiency with a 1.5 dB bandwidth of 10%, and 50% midband efficiency with a 1.5 dB bandwidth of 6%.

Constant rf drive results included 200 MHz of bandwidth with minimum efficiency of 33% and 36 dB gain at the 800 kW level, and 200 MHz of bandwidth with minimum efficiency of 34% and 37 dB gain at the 1100 kW level.

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LIST OF ILLUSTRATIONS

I. INTRODUCTION

This final report on Contract F30602-75-C-0080 describes work accomplished during the period 16 December 1974 through 30 June 1976.

The program consisted of the continuation, as Phase II, of a theoretical and experimental investigation into methods of improving the conversion efficiency of relatively broadband linear-beam amplifiers at peak power levels in the vicinity of 1 MW.

The vehicle for Phase II was an S-band Twystron® amplifier which used the gridded gun, collector and output window from the Phase I tube. The klystron input section and cloverleaf coupled-cavity output section designs were similar to those of the Phase I tube.

The program effort consisted of the evolution of a cloverleaf design optimized for impedance and phase characteristics. The optimized cloverleaf was then utilized in a series of paper designs of the Twystron. A computer analysis was performed on each design and the computer-predicted, large-signal performance was then used to guide the sequence of modifications of the paper design. A peripheral, but nonetheless major, effort was expended in measuring, identifying and selectively loading higher-order mode resonances.

A final design was settled upon and the Twystron was built. Testing was performed at the design operating conditions and then over a range of operating conditions. The test results have been analyzed.

The goal of the program was a significant improvement over the performance levels of the Phase I tube. Specific goals included a constant rf drive bandwidth of 10% with a minimum efficiency of 40% within that band.

The effort to meet that goal included the use of the short-stack, intense-interaction, coupled-cavity structure. The interaction impedance of the individual cloverleaf cavities was increased and the higher-order modes were selectively loaded by lossy resonant cavities.

The predicted performance of the final design chosen for construction was a 10%, constant-drive bandwidth with efficiencies of 43% at band edge and 57% at midband.

II. DESIGN

A. PRINCIPAL OPERATING PARAMETERS

The basic operating parameters were chosen for the previous program, Phase I, to be in a region of practical interest to the USAF. There were no new major considerations, and the basic operating parameters remained unchanged. Principal design parameters are given in Table 1.

TABLE 1

PRINCIPAL DESIGN PARAMETERS

Beam Voltage	78 kV
Beam Current	32.4 A
Beam Power	2.52 MW
Microperveance	1.50
Center Frequency	3300 MHz
Bandwidth (1 dB)	330 MHz
Power Output (Band Edge)	1.0 MW
Gain	30 dB
Duty	0.001
Pulse Width	10 μsec
γa	0.958 radian
$B_e d$ (Klystron Cavities)	1.50 radian
R/Q (Klystron Cavities)	120
Bq	18.7°/in
Brillouin Field	502 gauss
Design Field	1250 gauss
Grid Bias	-1000 V
Grid Pulse	2500 V

B. OVERALL TUBE DESIGN

The specific design, in the sense that it is an S-band Twystron, remained unchanged from Phase I. The details of completely unchanged subassemblies are included below for completeness.

A reduced copy of the layout drawing is shown in Figure 1.

The gridded gun is a design used on a megawatt S-band klystron. It has a forward μ of 30 and will operate over a wide range of perveance and beam voltage in the 70 kV - 90 kV range. The availability of this gun was the deciding factor in choosing a tunnel diameter of 0.625" for the Phase I tube. This gun was re-used for the present Phase II tube.

The klystron section consists of seven cavities, which is one more than the Phase I tube. The addition of this extra cavity was required to achieve a minimum gain in excess of 30 dB. Cavity No. 1 is externally loaded by the input loop. Cavities No. 2, No. 3 and No. 4 are externally loaded by loop-coupled coaxial loads. The first five cavities, comprising the low-level gain portion of the klystron section, are broadband tunable with inductive wall tuners. The last two cavities, comprising the high-level bunching portion of the klystron section, have trim tuners locked in place. Their tuning was never changed during hot test. The preset frequency distribution of the seven-cavity klystron section is shown in Table 2.

TABLE 2

SEVEN-CAVITY DISTRIBUTION

Cavity No.	1	2	3	4	5	6	7
Frequency (MHz)	3150	3350	3280	3435	3468	3515	3525

The cloverleaf output circuit consists of eleven circuit plates. The distribution of these circuits by type is shown in Table 3.

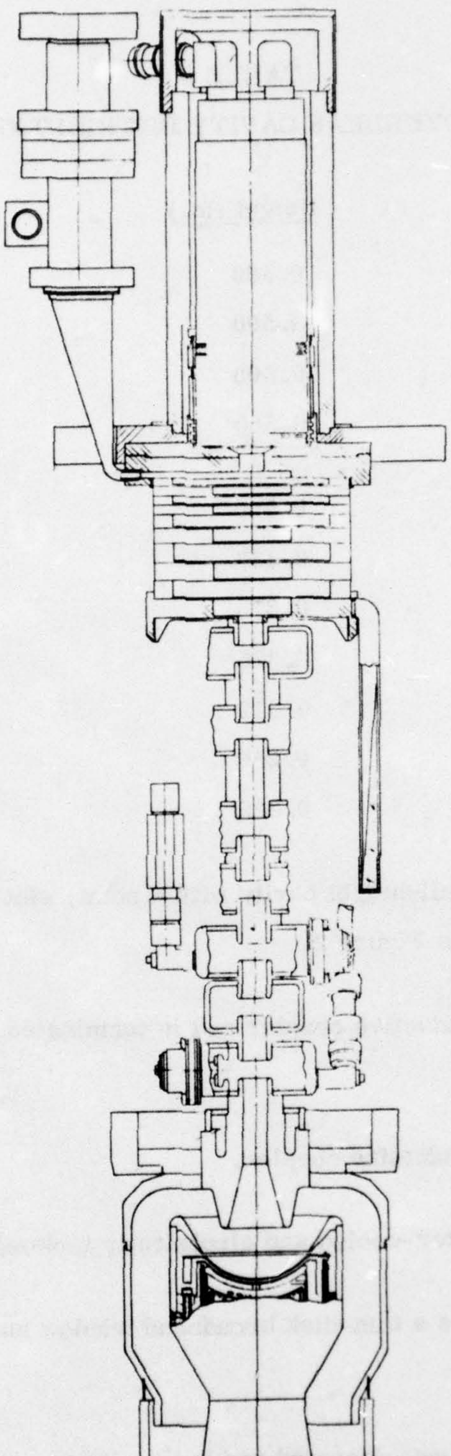

Figure 1. Tube Outline

TABLE 3

CLOVERLEAF CAVITY DISTRIBUTION

Cavity No.	Height (In.)	Mode Loading
1	0.500	Sever
2	0.500	Light Kanthal
3	0.500	π, Slot, 5H
4	0.500	π, Slot, 5H, Light Kanthal
5	0.500	π, Slot, 5H
6	0.437	None
7	0.375	Light Kanthal
8	0.375	None
9	0.312	None
10	0.250	None
11	0.225	Output

A photograph of a full-height cavity with π point, slot mode and 5H mode loading cavities is shown as Figure 2.

The sever has an inductive coupler and is terminated in a matched load of BeO-SiC.

The output has an inductive coupler.

The collector is water-cooled and electrically isolated from the tube body.

The output window is a thin-disk broadband window and was reused from Phase I.

A focusing solenoid was designed and built. It has six individual wire-wound coils to provide beam control flexibility.

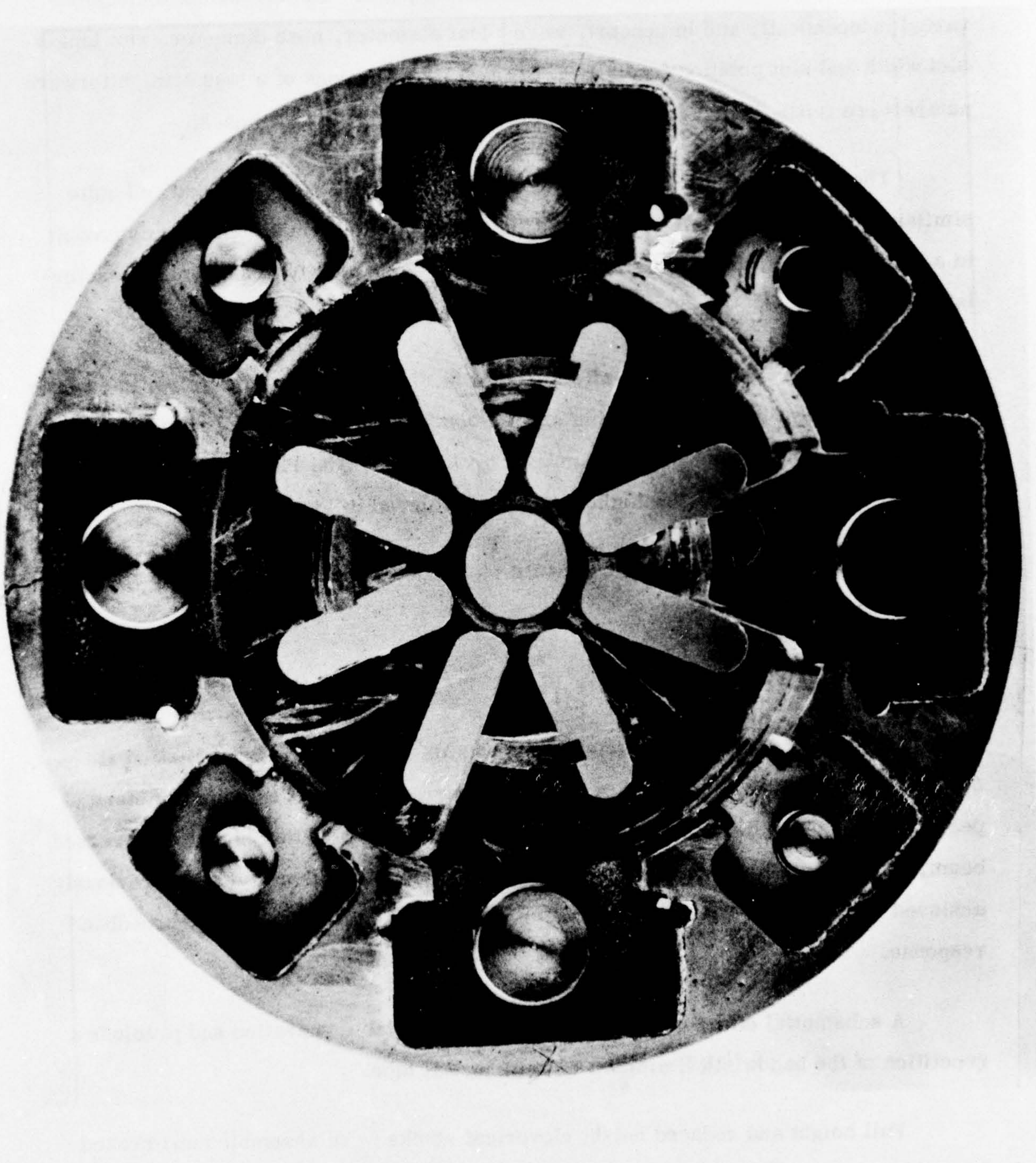

Figure 2. Photograph of Cloverleaf with Mode Loading Cavities

C. CLOVERLEAF DESIGN

The Phase I design was taken as a starting point. The cloverleaf dimensions, varied independently and in concert, were: leaf diameter, nose diameter, slot length, slot width and slot position (radially). Several modifications of a less straightforward nature were tried, including nonuniform slot width and vane type noses.

The design providing the best characteristics was straightforward and quite similar to the Phase I design. The multitudinous variations in dimensions did result in a higher R/Q and interaction impedance for the same quality dispersion characteristic.

The dispersion characteristic is shown in Figure 3. The interaction impedance (at $r = a$) is shown in Figure 4. This may be compared to the Phase I results given at $r = o$ by multiplying the Phase I numbers by Jo^2 (ka). The Phase II impedance at midband is approximately 18% higher than was achieved in Phase I.

The impedance of the taper circuits was achieved with a reduction in slot length of not more than 4%.

D. STABILITY

The major defect in the Phase I tube was its instability. An oscillation at 6498 MHz was sufficiently strong to prevent rf operation at the design parameters of perveance and beam diameter. While it was possible, even with a highly compressed beam, to get sufficient data to demonstrate higher efficiency than had been previously achieved with a broadband circuit, it was not possible to get a completely broadband response.

A substantial effort was undertaken to assure stable operation and preclude a repetition of the bandwidth limitation of the Phase II tube.

Full height and reduced height cloverleaf stacks were assembled and brazed for cold test. The higher-order modes were excited, the field patterns measured and resonances identified.

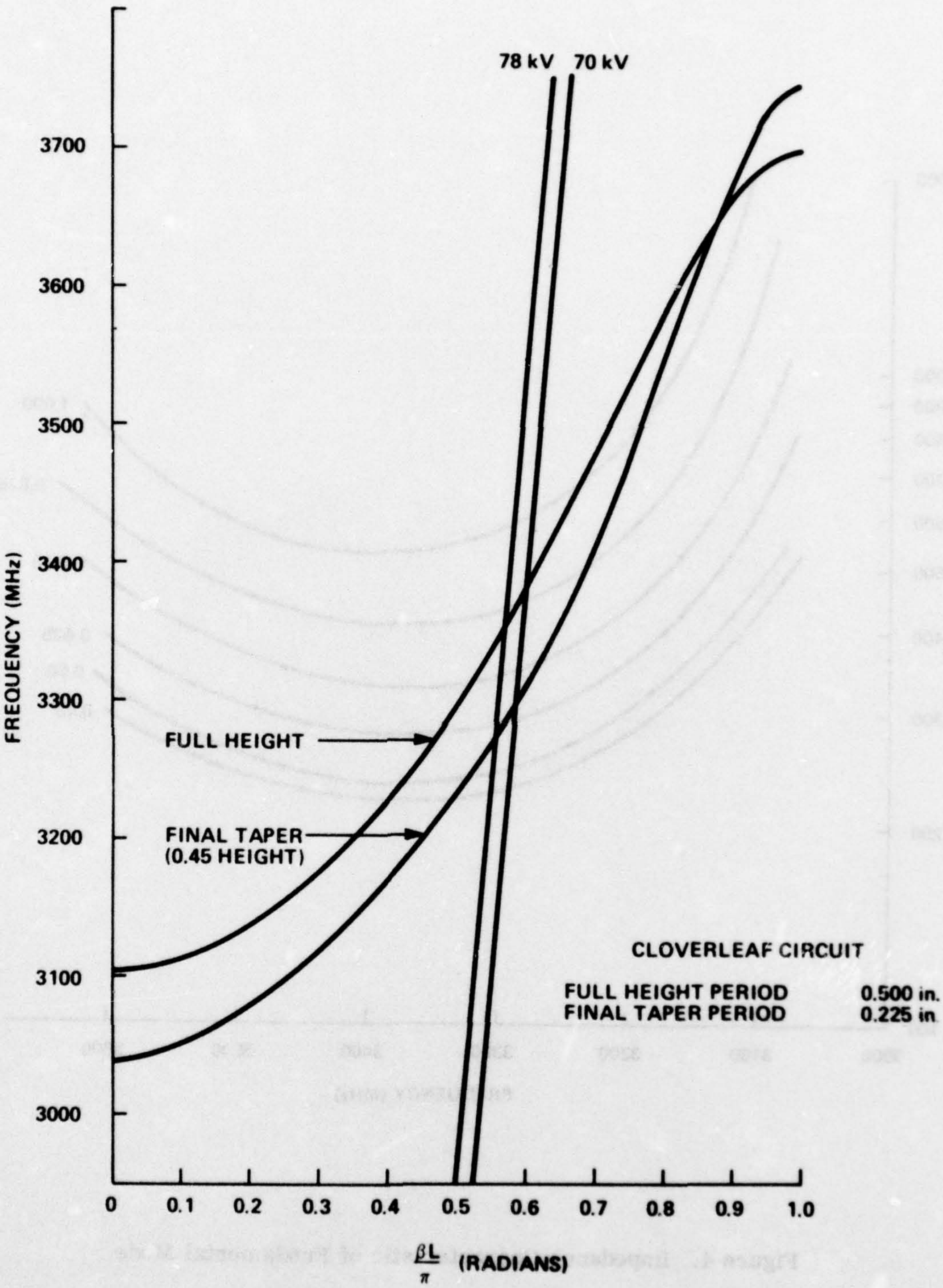

Figure 3. Dispersion Characteristic of Fundamental Mode

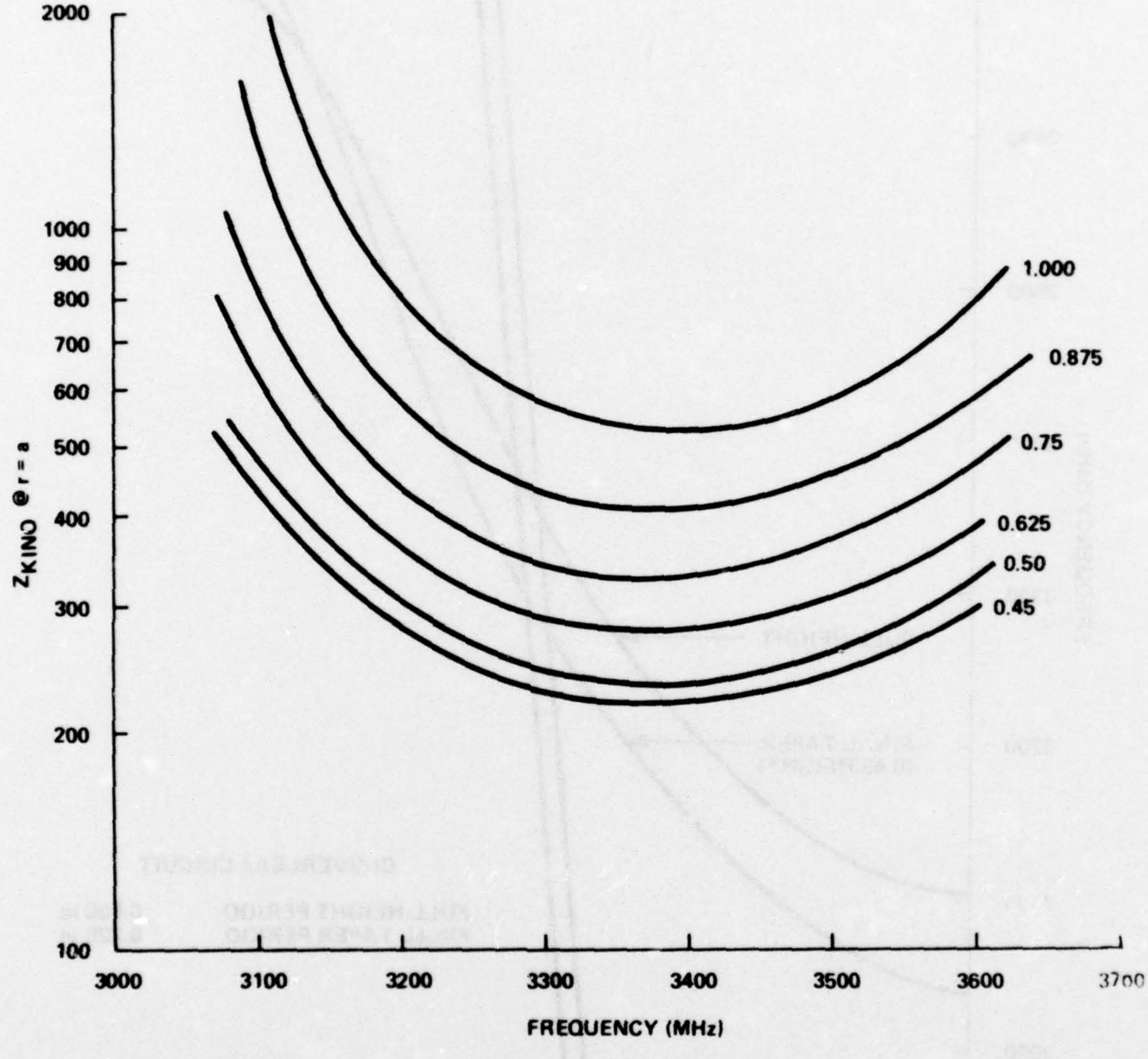

Figure 4. Impedance Characteristic of Fundamental Mode

Lossy resonant cavities were milled into the noses and leaves of the cloverleaf cavities. This was an iterative procedure since the presence of the loading cavities alters the frequencies of the modes. The resonant cavities, milled into the noses and tuned to load the π resonance of the fundamental mode, lowered the slot and 5H modes substantially. A lesser, but still significant, lowering of the 5H mode was caused by the leaf cavities tuned to load the slot mode.

The dispersion characteristics of the slot and 5H modes are shown in Figure 5, along with the fundamental mode and the beam voltage line for overall perspective.

The effect of the nose cavities loading the π point of the fundamental mode is shown in Figure 6.

The slot mode dispersion characteristics are shown in detail in Figure 7.

The effect of the slot mode loading cavities is shown in Figure 8.

The 5H mode dispersion characteristics are shown in Figure 9. The 7/8 and 3/4 height taper cavities had characteristics virtually identical to those of the plain, full-height cavities.

The effect of the 5H mode loading cavities is shown in Figure 10.

E. LARGE-SIGNAL ANALYSIS

The starting point for the Phase II design was the design chosen and tested in Phase I.

An additional klystron cavity was immediately added to increase the gain of the tube.

The cold test data taken on the klystron cavities and the cloverleaf cavities were input to the several computer programs that are ancillary to the large-signal program. The outputs of these programs are the inputs to the large-signal program. The beam parameters were the same as they were in Phase I.

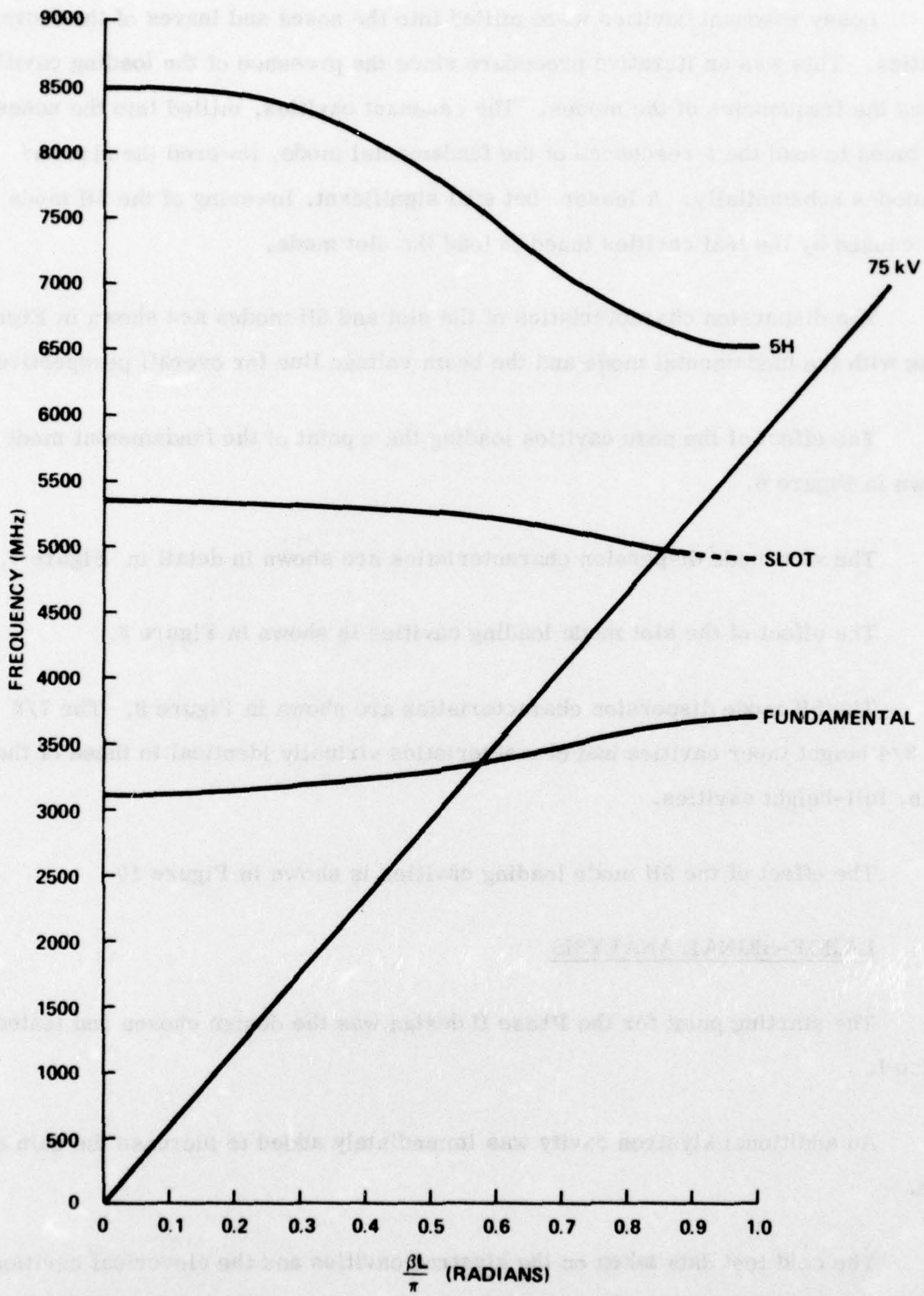

Figure 5. Dispersion Characteristics of Higher Order Modes

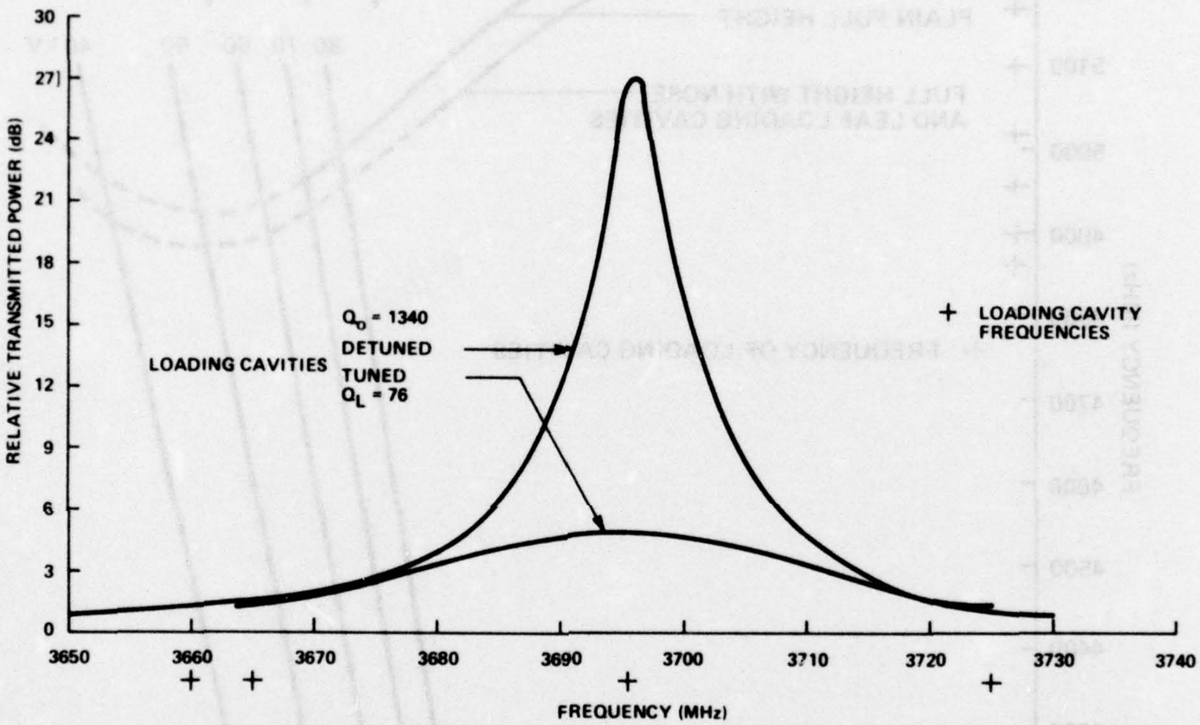

Figure 6. Fundamental Mode π Point Loading

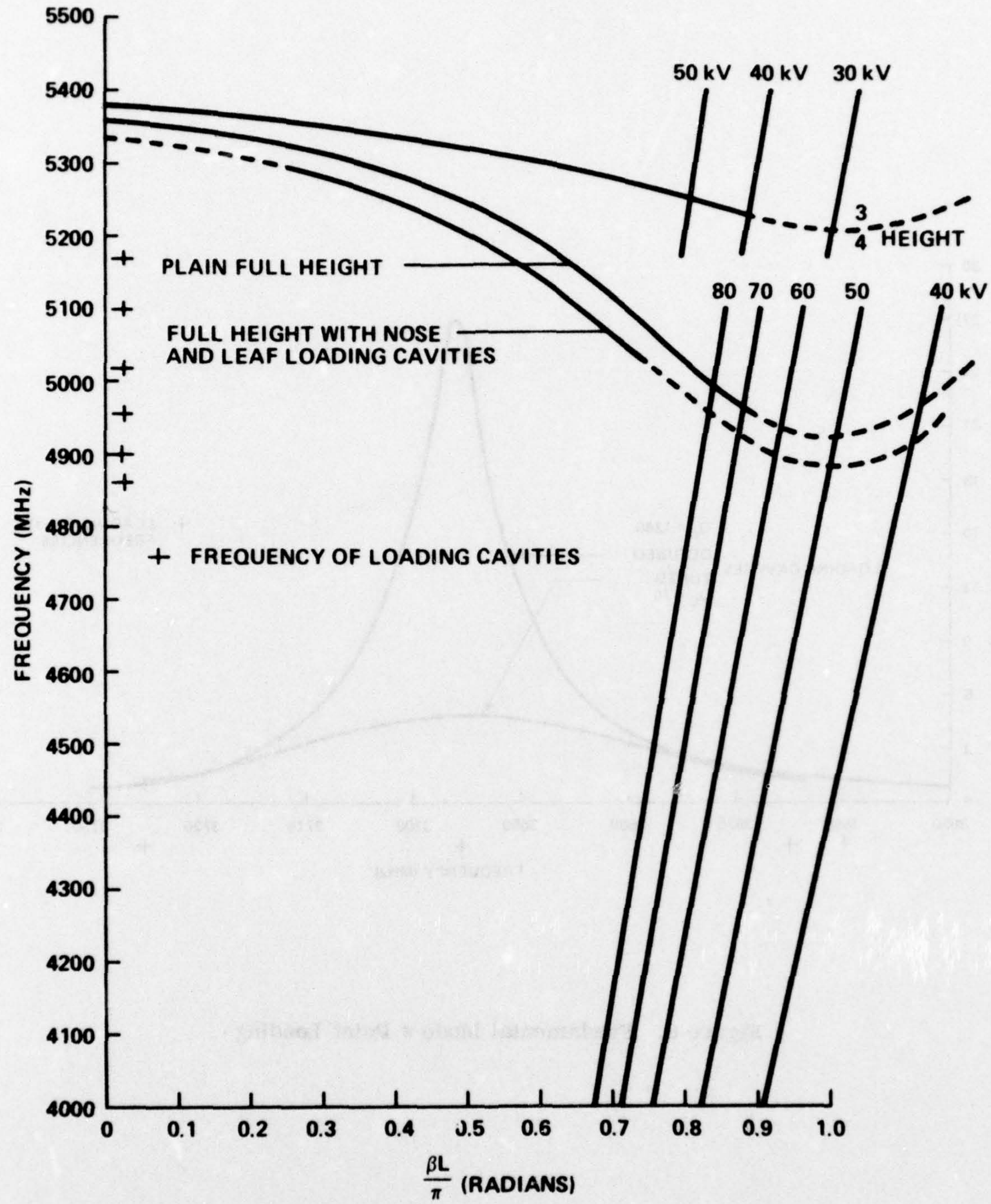

Figure 7. Slot Mode Dispersion Characteristic

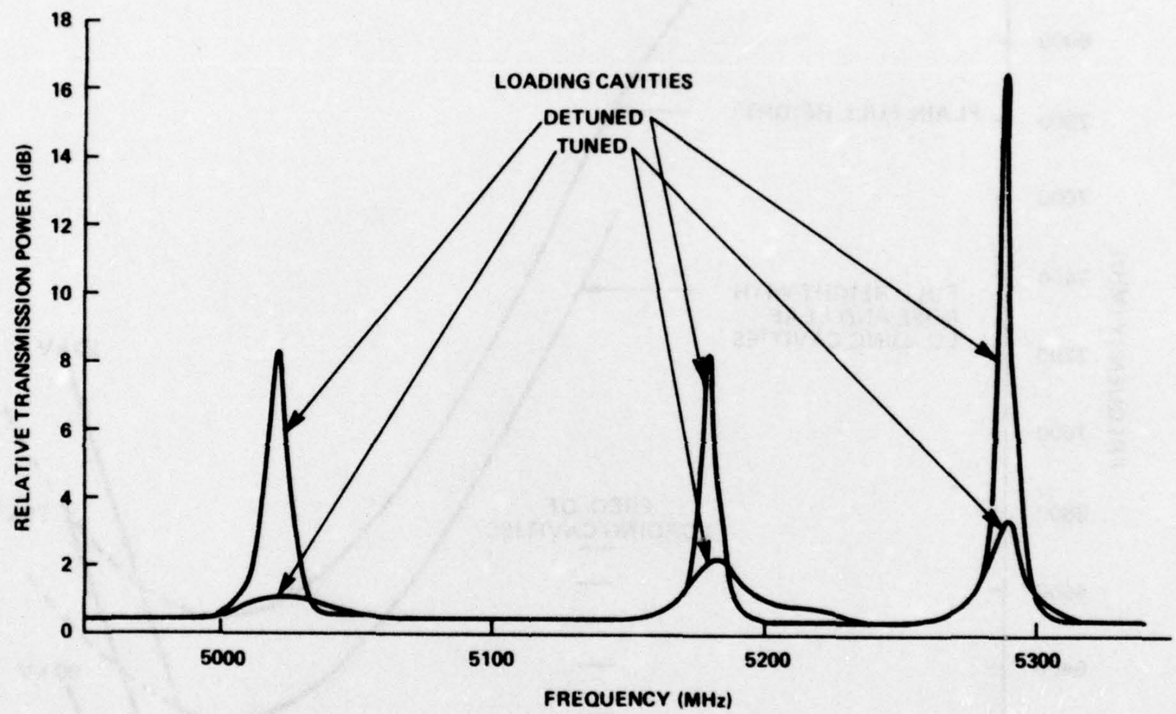

Figure 8. Slot Mode Loading

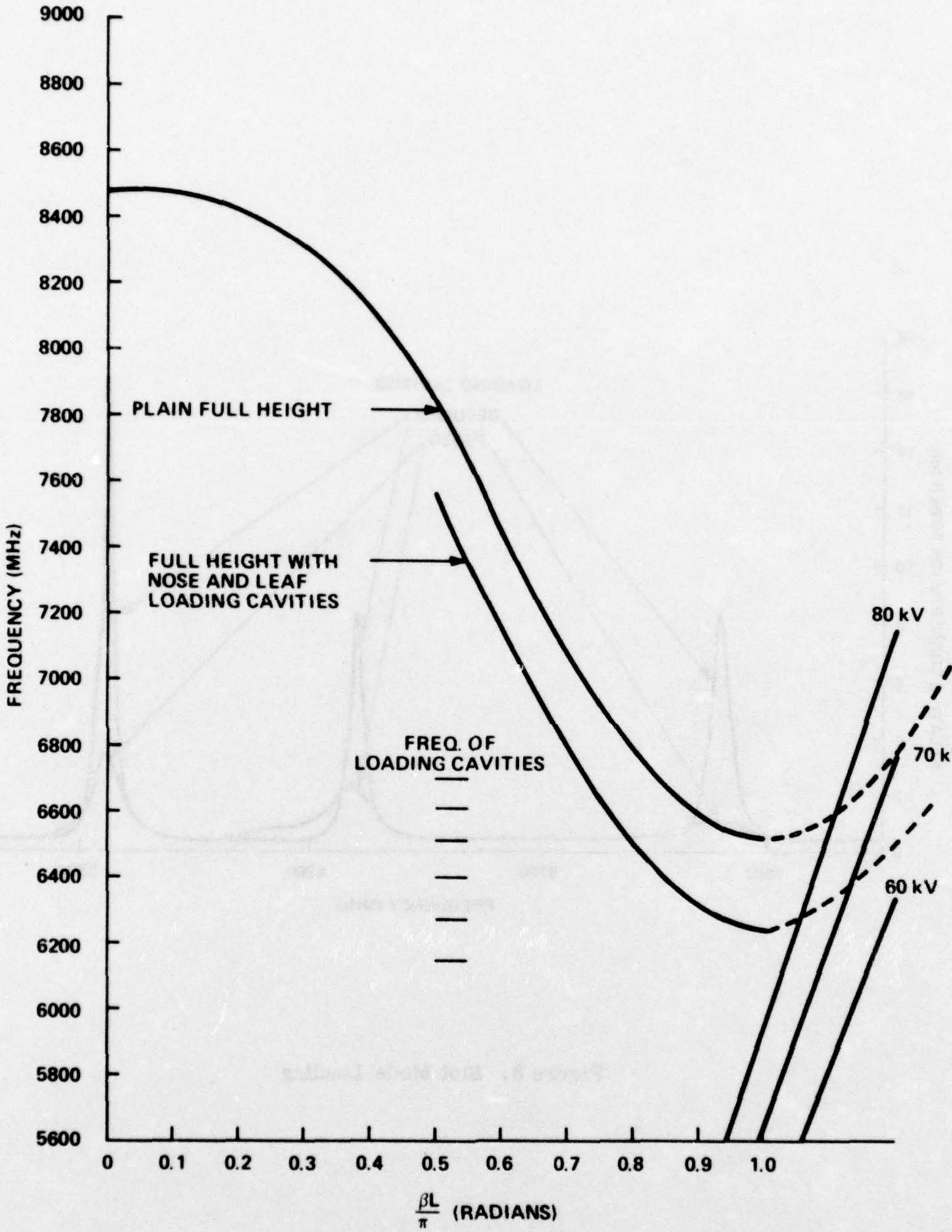

Figure 9. "5H" Mode Dispersion Characteristic

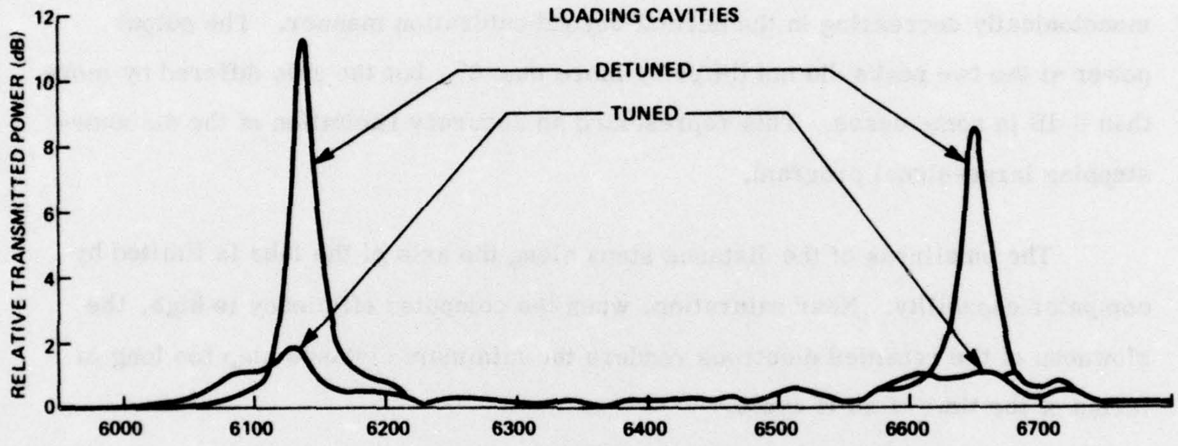

Figure 10. "5H" Mode Loading

The standard technique of achieving a tentative optimum at midband and then doing a broadband analysis was used. Modifications suggested or demanded by the response at some frequency were then made and the analysis was repeated. This was continued, with continuously updated input data from cold test work proceeding simultaneously.

As the optimum was approached and the computer analysis was being made at and in the vicinity of saturation, the predicted behavior showed anomalous gain. The power output reached a peak at some value of rf drive. As the drive was increased, the output power decreased and then increased to a second peak before monotonically decreasing in the normal beyond-saturation manner. The output power at the two peaks did not differ by more than 3%, but the gain differed by more than 6 dB in some cases. This represented an accuracy limitation of the distance-stepping large-signal program.

The smallness of the distance steps along the axis of the tube is limited by computer capability. Near saturation, when the computed efficiency is high, the slowness of the retarded electrons renders the minimum distance step too long in terms of the time of an rf cycle.

All computations were then made with the time-stepping large-signal program. The ambiguity of the two efficiency maxima was resolved and the final optimization of the output circuit completed.

The computer-predicted efficiency for the final design is shown as a function of frequency in Figure 11. A sample of a computer-generated electron phase plot is shown in Figure 12, with the attendant beam currents and cavity voltages shown in Figure 13.

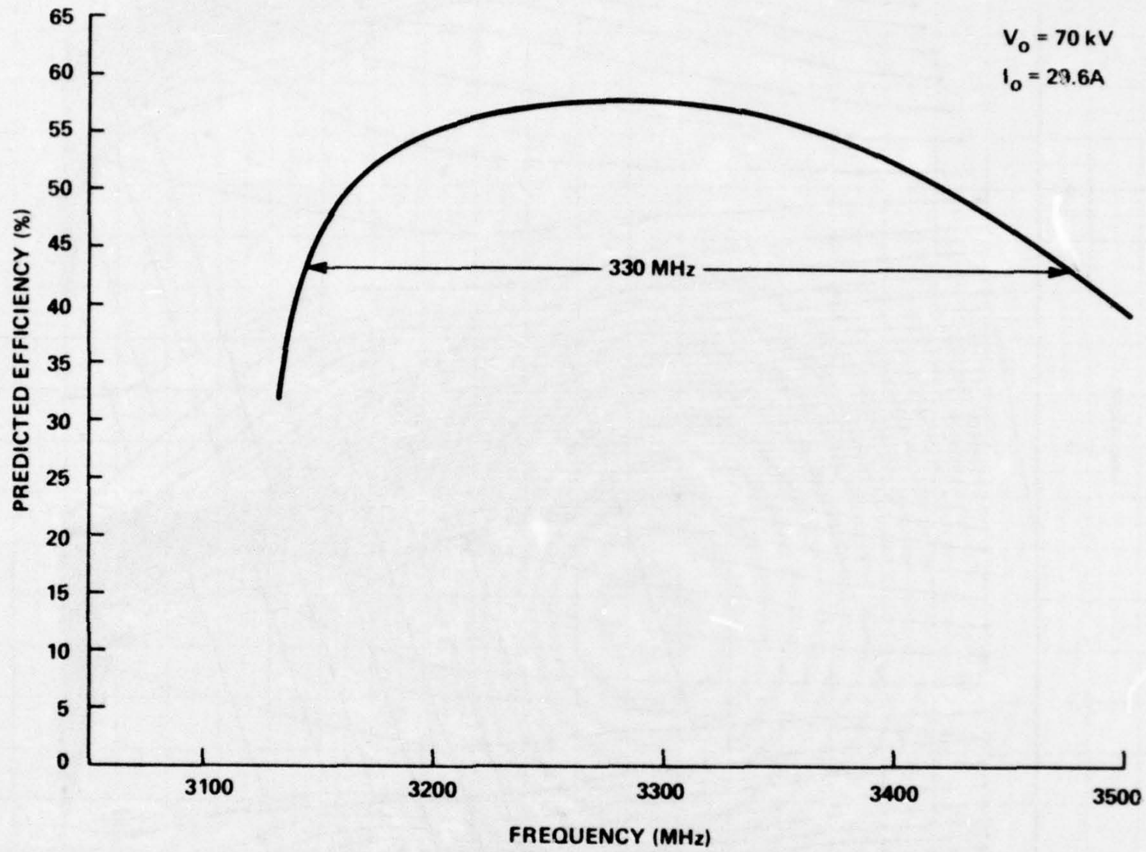

Figure 11. Computer Predicted Efficiency vs Frequency

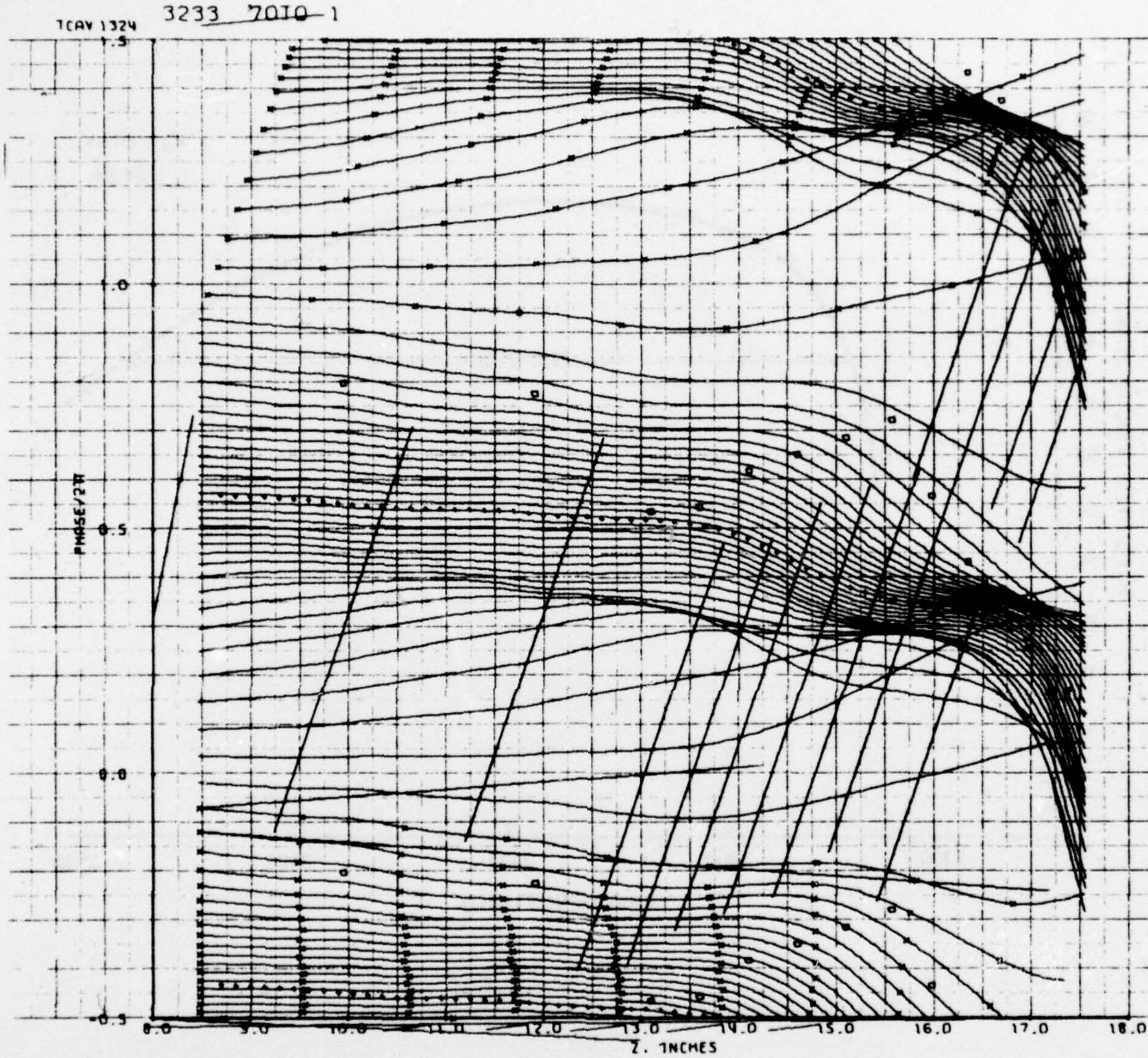

Figure 12. Electron Phase Plot

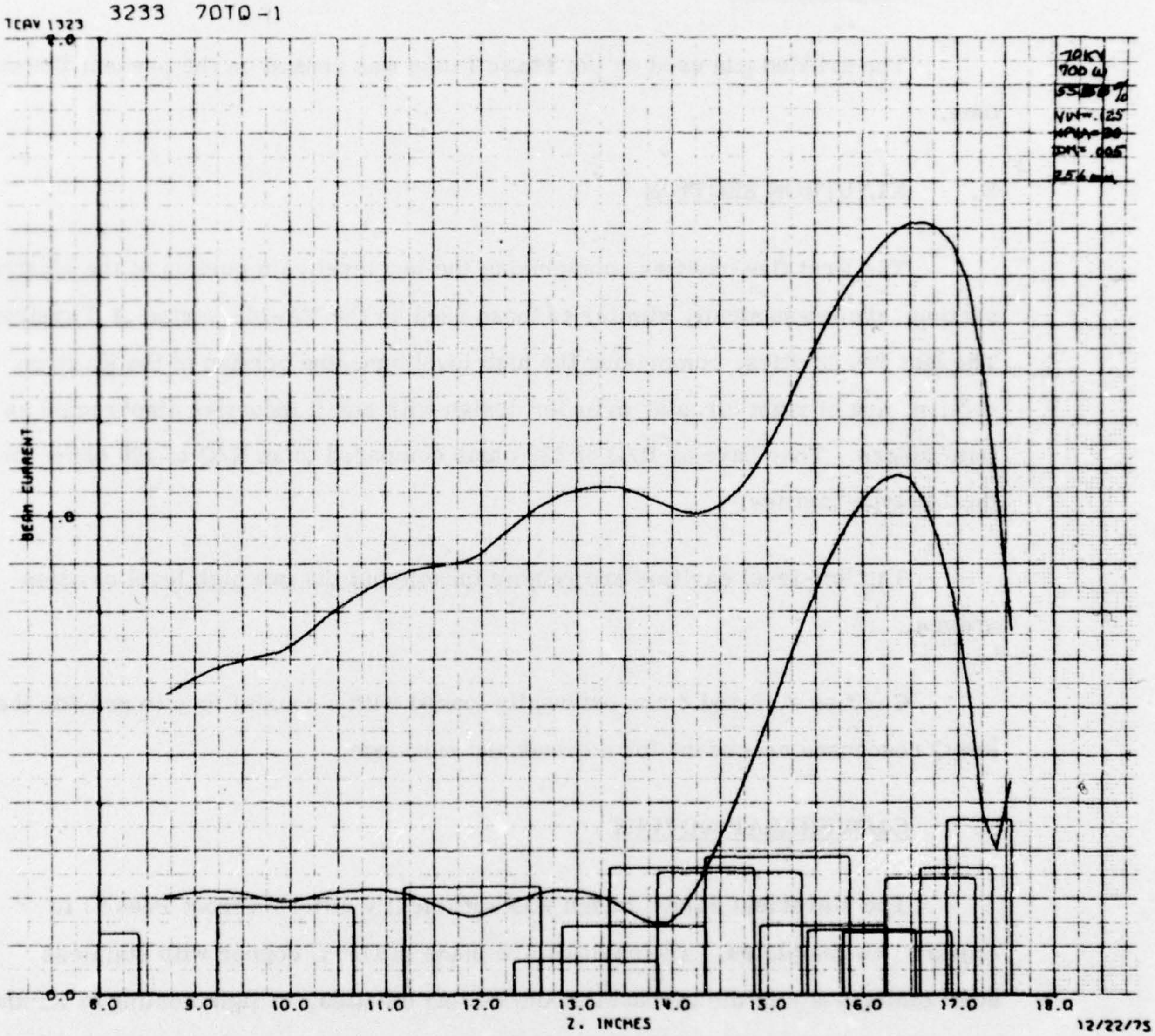

Figure 13. RF Beam Current and Cavity Voltage

III. CONSTRUCTION OF EXPERIMENTAL TUBE

A. GRIDDED GUN

The gridded gun used on the Phase I tube was reused on the present Phase II tube.

B. KLYSTRON SECTION

The first five cavities, comprising the low level gain portion of the klystron section, are mechanically similar to those used on the VA-145 series of Twystrons. The last two cavities, comprising the high level bunching portion of the klystron section, are of right circular cylinder design with small inductive diaphragms as trim tuners. They have an R/Q of 139 ohms compared to an R/Q of 120 ohms for the 145 type cavities.

The low-level cavities are remote tunable but the two high level cavities are not.

Cavities 2, 3 and 4 are externally loaded with a coaxial loop to provide the low Q responses necessary for a broadband response.

C. CLOVERLEAF OUTPUT

The cloverleaf cavity design was sufficiently different from Phase I to require new templates. The cavities are made of OFHC copper with stainless steel tuning posts in the resonant mode-loading cavities. A light coating of Kanthal was applied to the walls of these loading cavities and to the main circuit of cloverleaf cavities 2, 4 and 7.

The main stack braze was run with the tuning posts in cloverleaf cavity No. 5 left free. These were given a final adjustment in cold test and brazed at the same time as the sever coupler.

D. OUTPUT AND SEVER TRANSDUCERS

Both transducers provided inductive coupling to the output and sever ports. Subassembly and final assembly brazes caused no difficulties.

E. COLLECTOR

The collector is a standard, water cooled, electrically isolated model.

F. SEVER LOAD

The sever load consists of a BeO–SiC wedge that is metallized and brazed into a reduced height, water cooled, copper waveguide section.

G. OUTPUT WINDOW

The output window is the thin-disk circular window used for the Phase I tube.

IV. TEST RESULTS

A. GENERAL

The saturated output response of the tube is given in Figure 14 and shows a 1.5 dB bandwidth of 10% with a peak efficiency of 42.5%. The constant drive response is given in Figure 16 and shows a 1.5 dB bandwidth of 7% (230MHz) with a peak efficiency of 42% and a minimum gain of 36 dB. This performance at the one megawatt level is similar to that heretofore achievable only at multimegawatt levels.

While the performance of the Phase II tube as described above is substantially better than that of any previous efforts, it is also substantially poorer than the performance predicted and expected.

The peak efficiency at 70 kV and microperveance 1.5, the design operating condition, is 41% and was predicted to be 58%. The maximum efficiency achieved with this Twystron was 50% at microperveance 0.8. While this is an improvement over the maximum of 44% at microperveance 0.8 achieved by the Phase I tube, it should have been well in excess of 60%.

There are three secondary deficiencies in the Phase II tube which are well understood and amenable to straightforward correction.

- As shown in Figures 14, 26 and 28, there is a dip in efficiency near the low end of the band. This is caused by the slot length tapering. This tapering was reduced to 4%, as reported in contract status report No. 9, and clearly must be reduced further.

- There is a gain hole in band, shown in Figure 15, which has been established as being the zero associated with cavity 3. Movement of this zero to a frequency above the band requires only a reduction in its loaded Q.

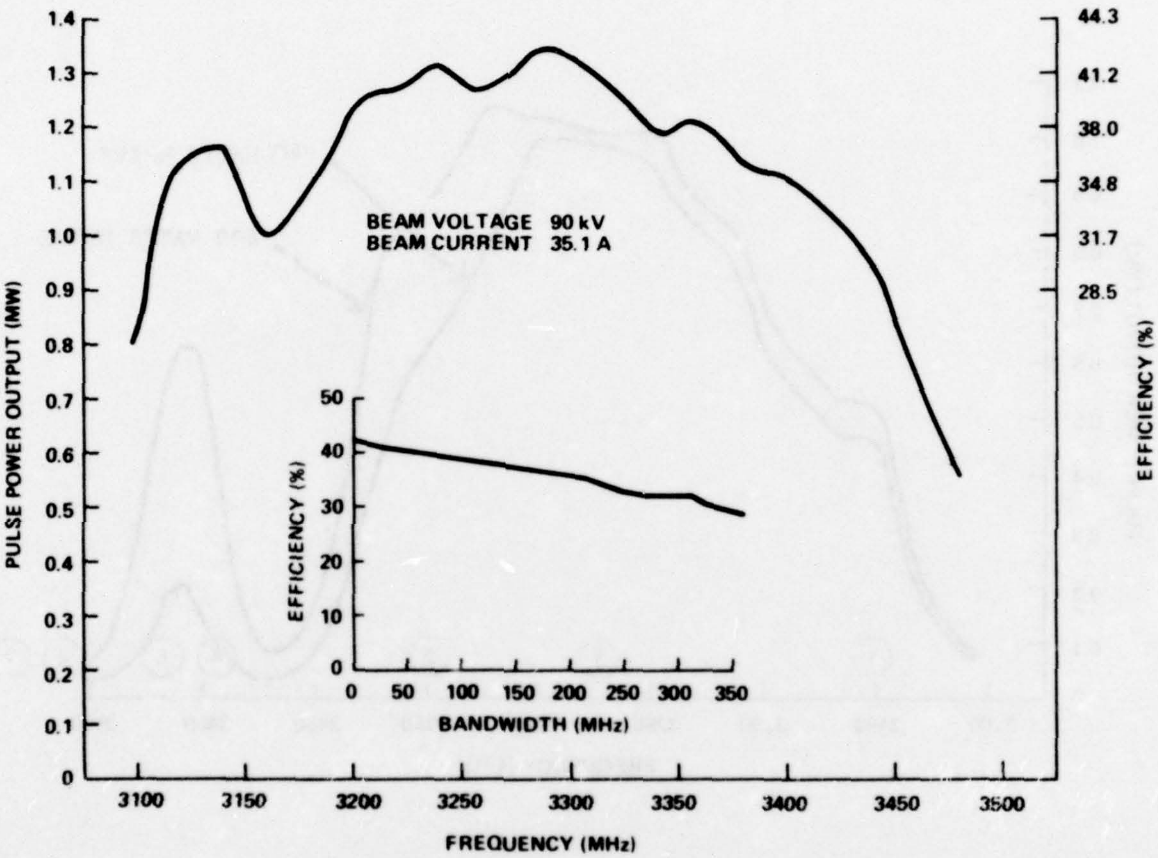

Figure 14. Saturated Power at 90 kV and 1.3 μperv

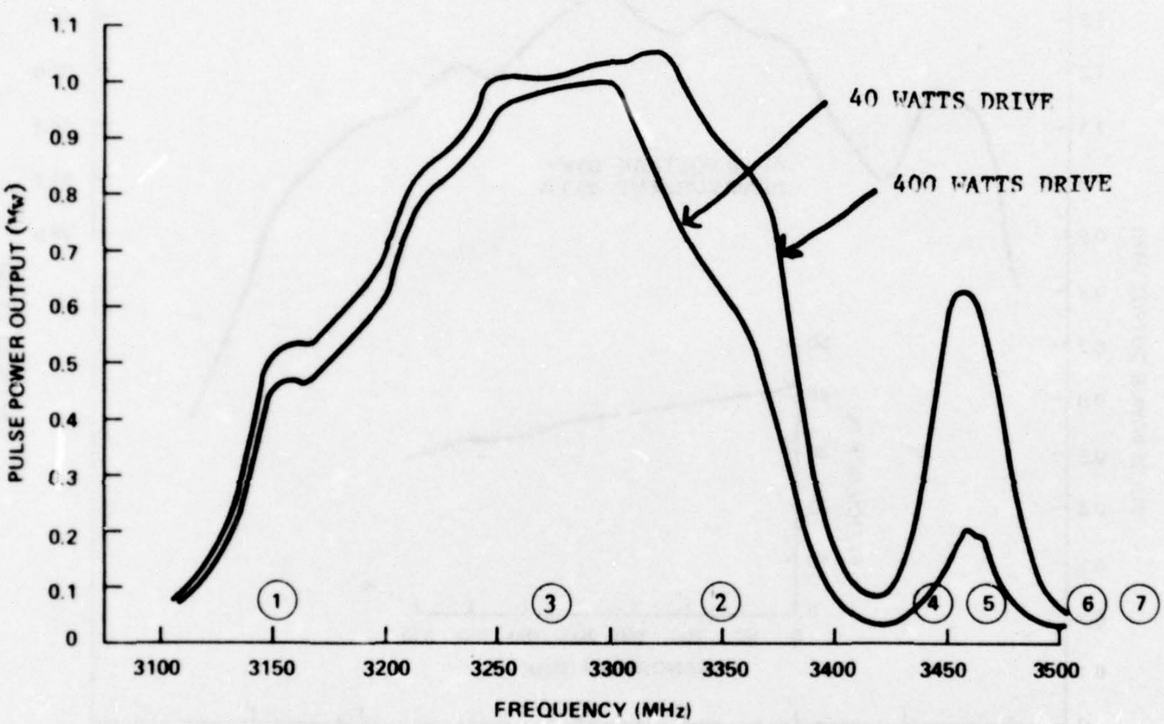

Figure 15. Gain vs Frequency at 90 kV and 1.3 μperv

- The tube is unconditionally stable under dc beam conditions at microperveance up to 1.9 at 80 kV, and 2.3 at 65 kV, the highest perveances the gun would provide at those voltages. There are, however, rf drive-induced oscillations near saturation that restrict operation under some combinations of beam voltage and current.

Each of these three deficiencies will be discussed in detail in the following subsections.

B. DETAILED DISCUSSION

1. Efficiency

The overall efficiency achieved across the band of interest, for a variety of sets of operating conditions, was approximately 30% at the bandedges and 40% at band center. These efficiencies are 0.7 of the values predicted and expected.

The efficiency dip is understood and solvable. The gain hole is even more easily understood and solvable. The drive-induced oscillations, primarily at 6368 MHz, require only the addition of an extra loading cavity. The correction of these three deficiencies will provide a smoother efficiency bandwidth and a constant drive bandwidth very close to the efficiency bandwidth, at perhaps slightly higher gain. All of the above will take place within the constraint of not much more than 40% band center efficiency, and 30% at the band edges.

The evidence indicates that the beam is smaller than assumed, and that this is a cause of the reduced efficiency. It is unclear whether or not this is sufficient in itself to account for the entire reduction.

An auxiliary coil was hung from the focusing solenoid and excited in a polarity to increase the cathode linking flux. The effect was clear at the low end of the band. The efficiencies for several values of auxiliary coil current are given in Table 4.

TABLE 4

EFFECT OF AUXILIARY COIL AT 3150 MHz,
80 kV, MICROPERVEANCE 1.4

I_{Aux} (A)	0	0.2	0.4	0.6	0.8	1.0	1.2
Eff. (%)	22	22.9	23.7	25.1	26.5	29.3	31.6

The increase lessened at the higher frequencies. At mid band, the increase was reduced to 2%. The gain at mid band increased by more than 3 dB with increasing I_{Aux}. This would lead one to expect a substantial increase in efficiency. It is possible that the drive-induced oscillations occurring near saturation clamped the efficiency at just over 40%. The effects of I_{Aux} at frequencies above mid band were very similar to the effects at mid band.

In the face of these drive-induced oscillations at and near saturation, all of the data presented, excepting that shown in Figures 28 and 29, are at reduced perveance.

The data shown in Figures 14 through 29 provide a solid view of the performance of the Phase II tube. Representative interpretations of the data in five of the figures are given below.

Figure 17 shows 1.0 MW output over 200 MHz at 35% efficiency and 32 dB gain.

Figure 21 shows 40% efficiency over a 160 MHz band at 27 dB gain.

Figure 23 shows 1.0 MW output over 150 MHz at 37% efficiency and 33 dB gain.

Figure 24 shows a saturated response with an efficiency of 38% over 200 MHz.

Figure 25 shows 38% efficiency over 140 MHz at 36 dB gain.

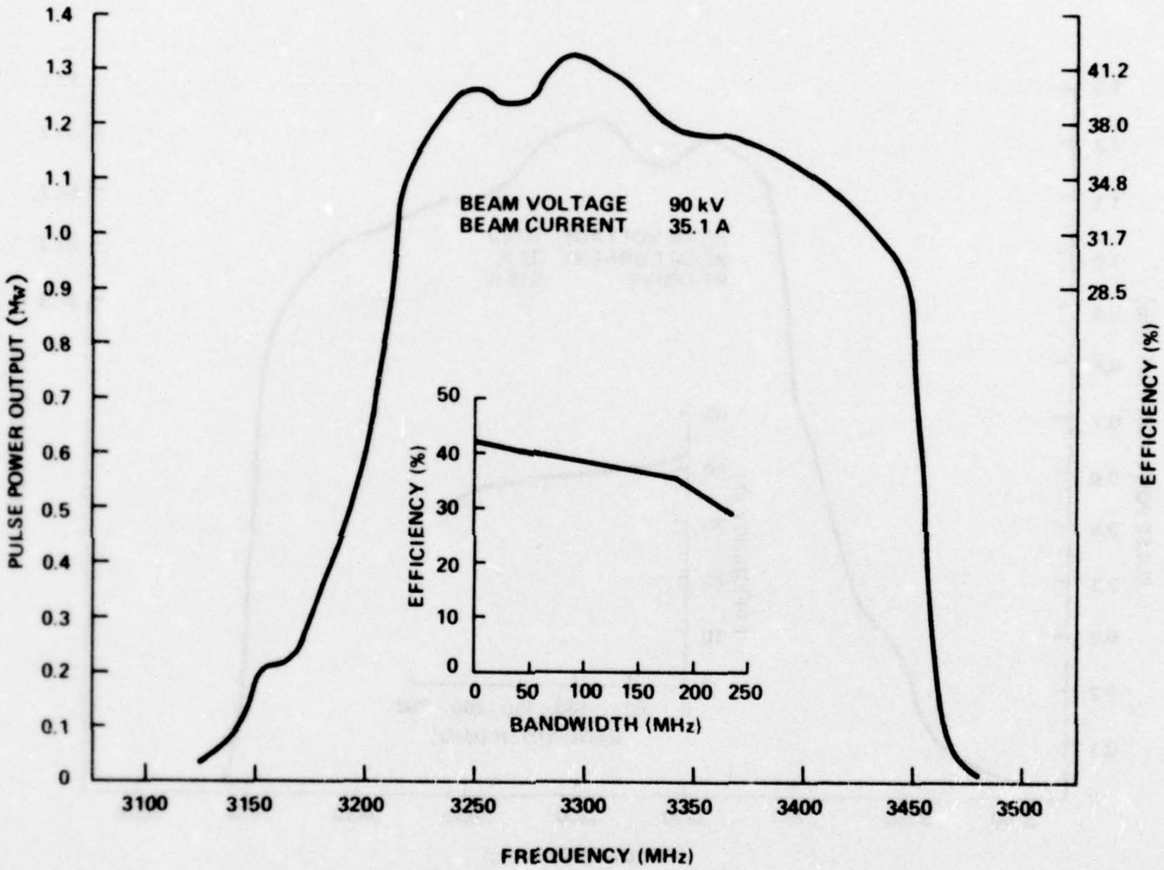

Figure 16. Constant Drive Power at 90 kV and 1.3 μperv

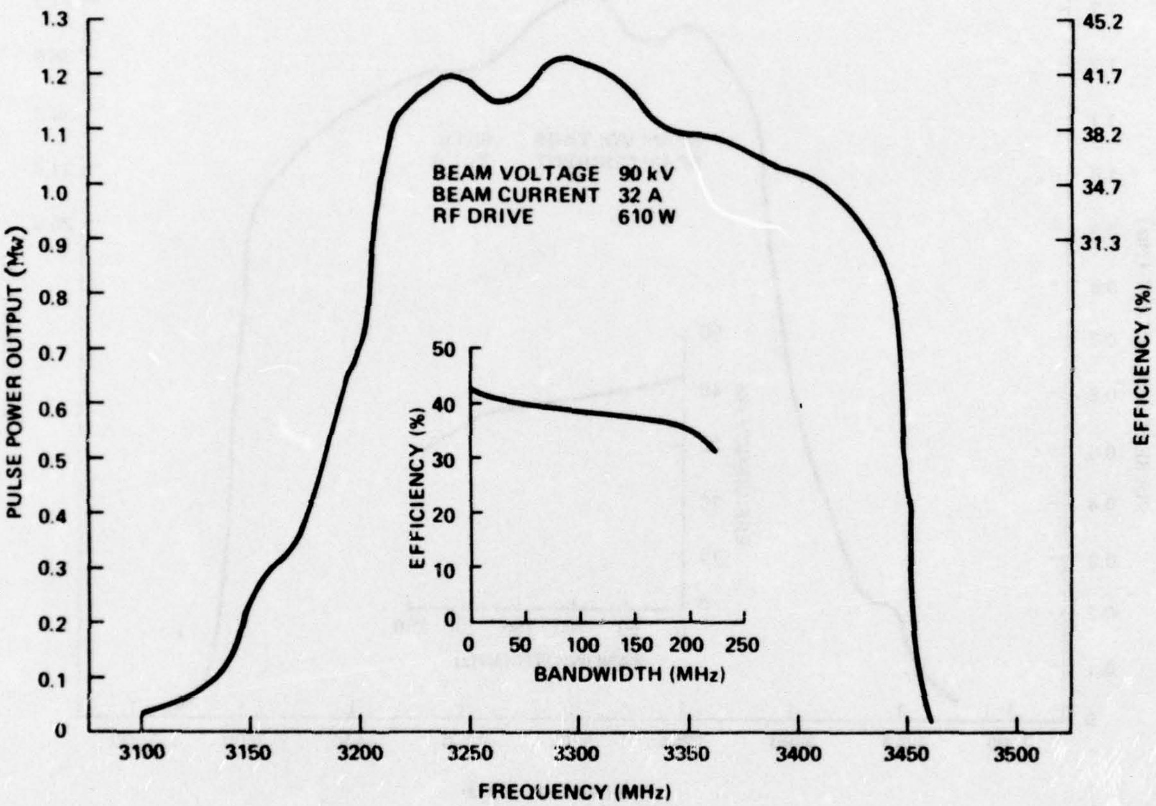

Figure 17. Constant Drive Power at 90 kV and 1.2 μperv

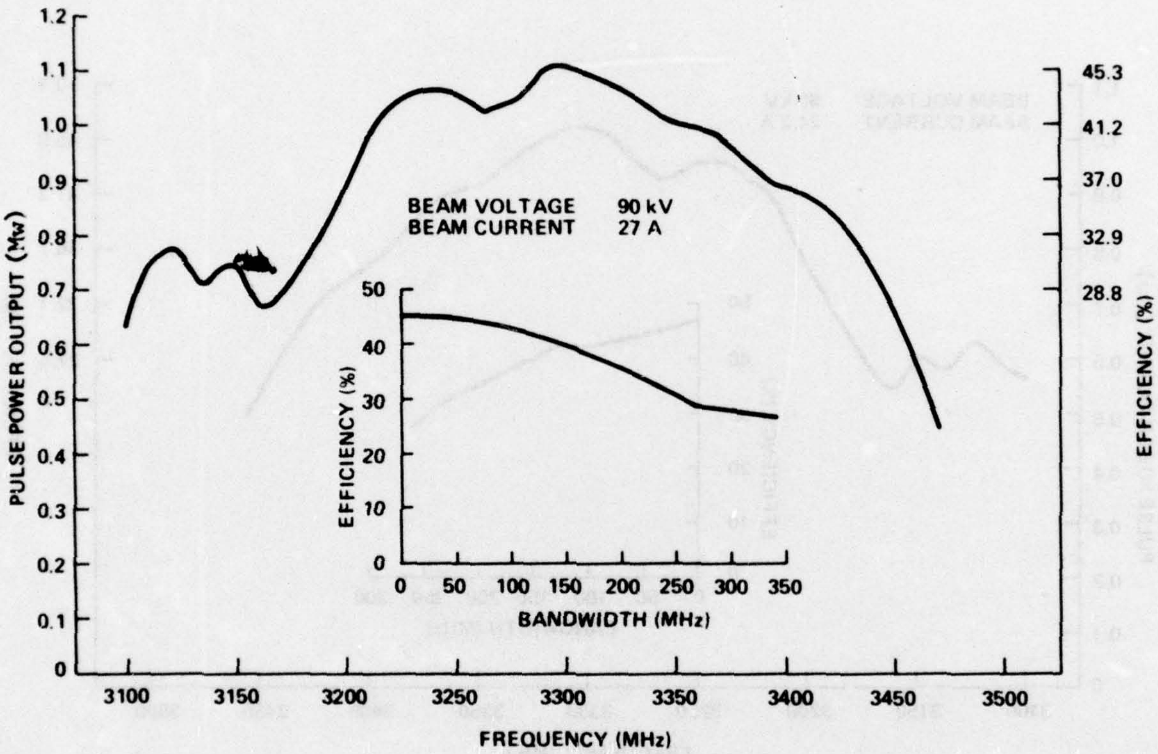

Figure 18. Saturated Power at 90 kV and 1.0 μperv

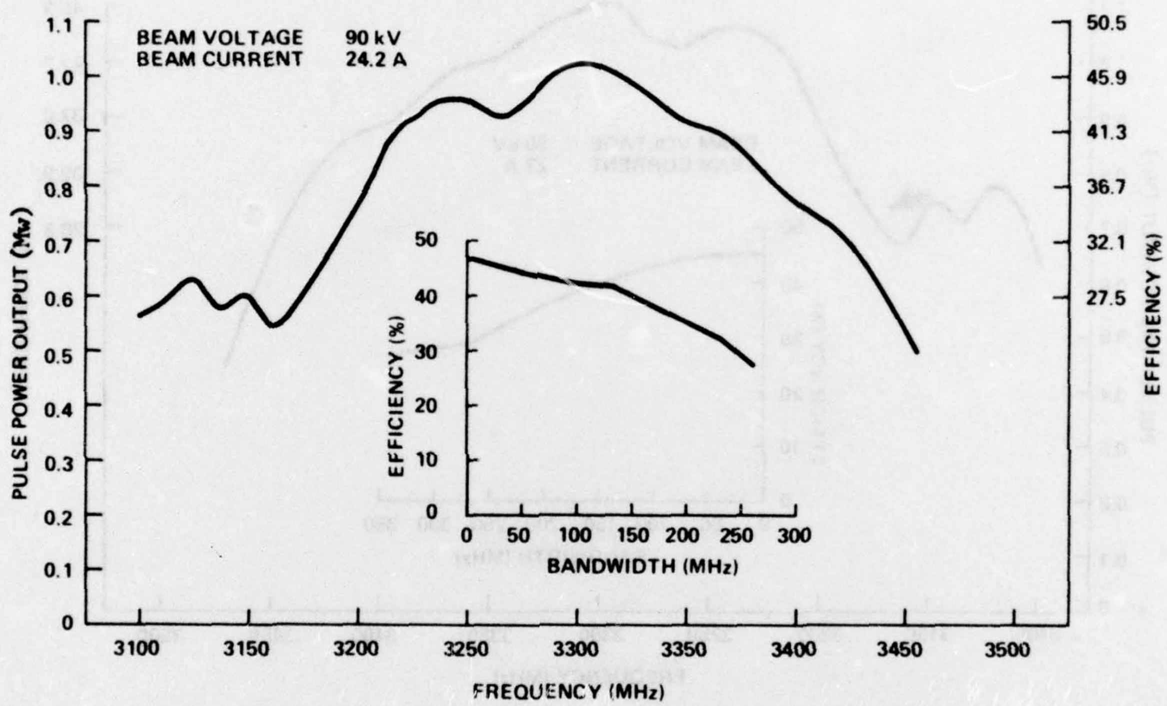

Figure 19. Saturated Power at 90 kV and 0.9 μperv

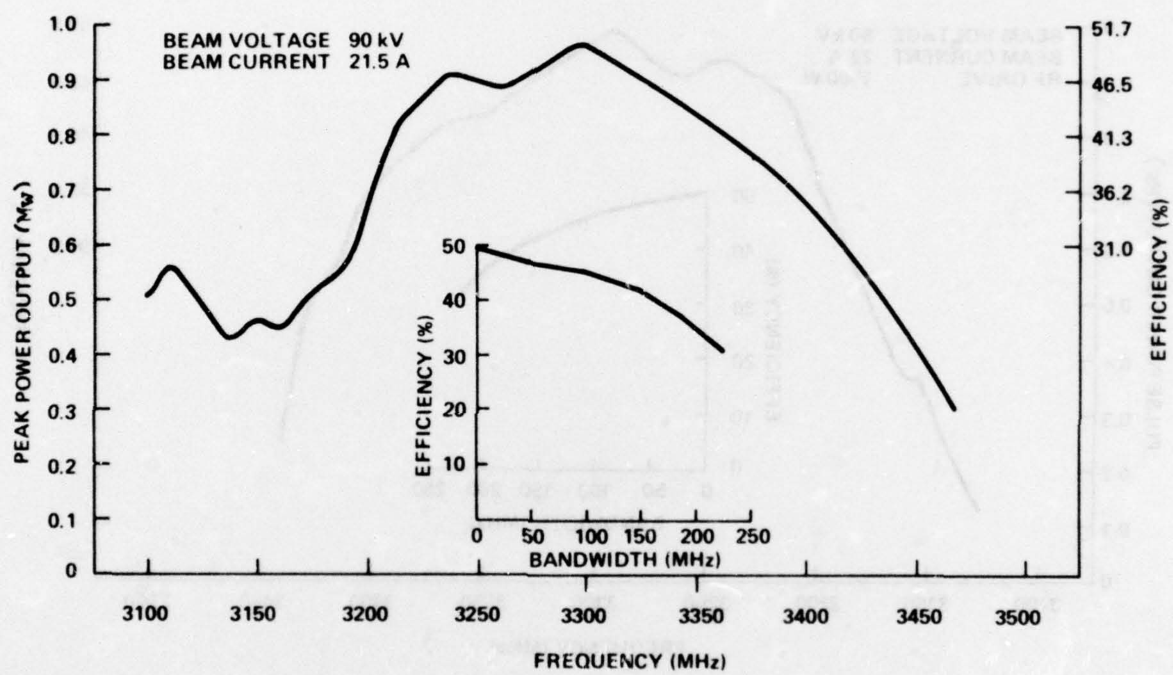

Figure 20. Saturated Power at 90 kV and 0.8 μperv

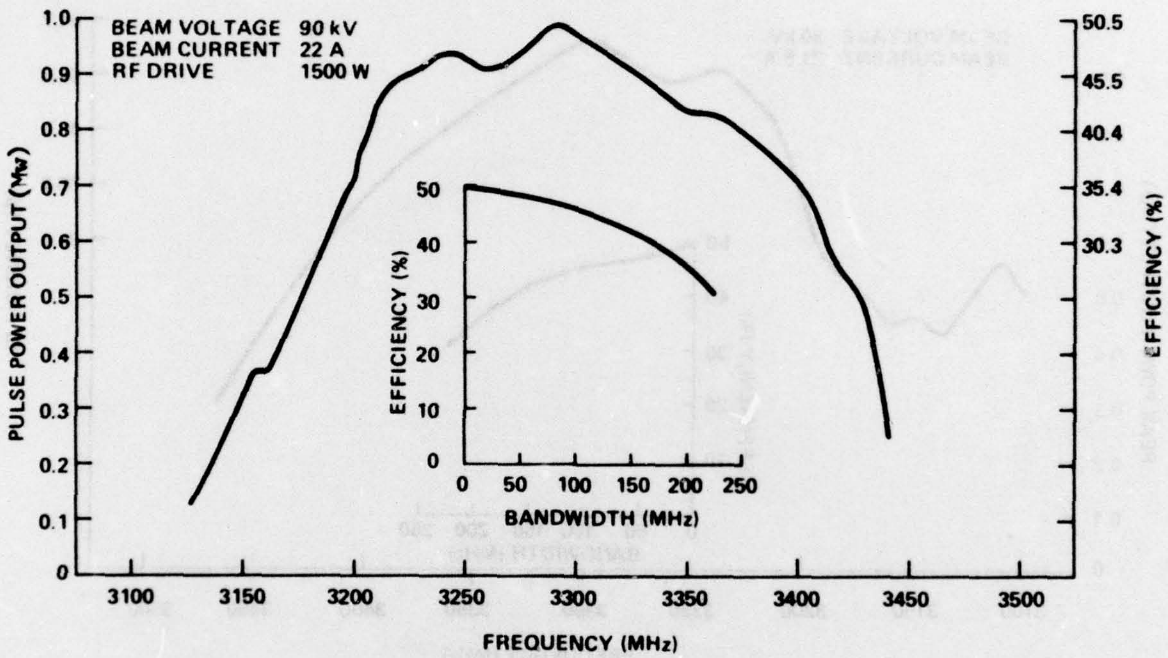

Figure 21. Constant Drive Power at 90 kV and 0.8 μperv

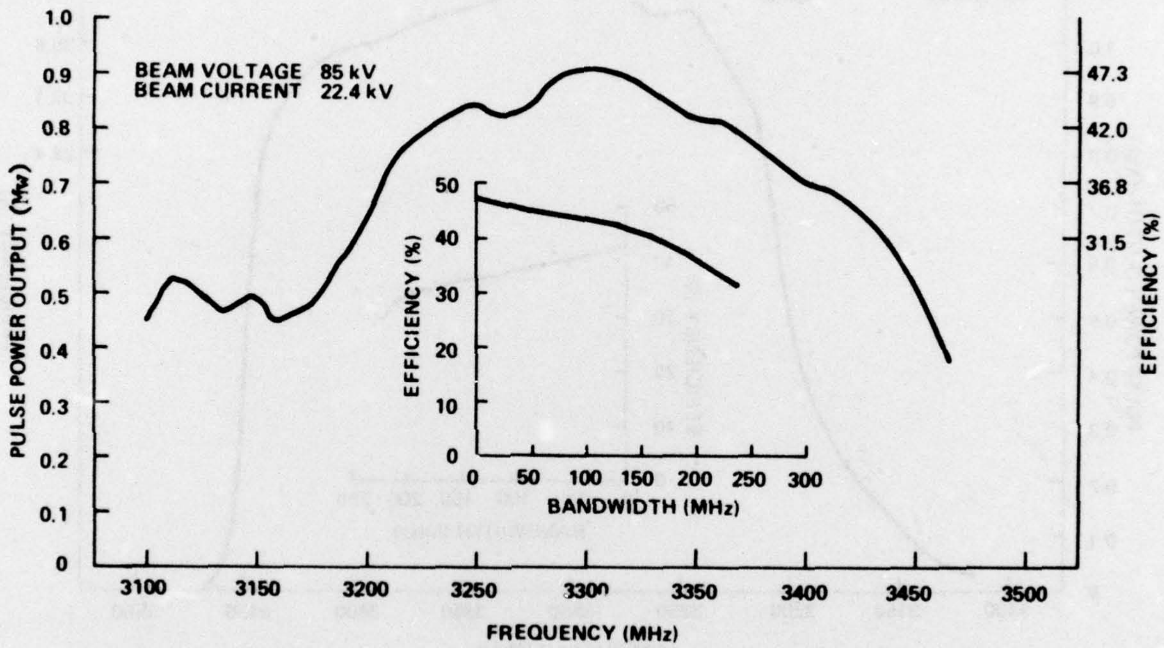

Figure 22. Saturated Power at 85 kV and 0.9 μperv

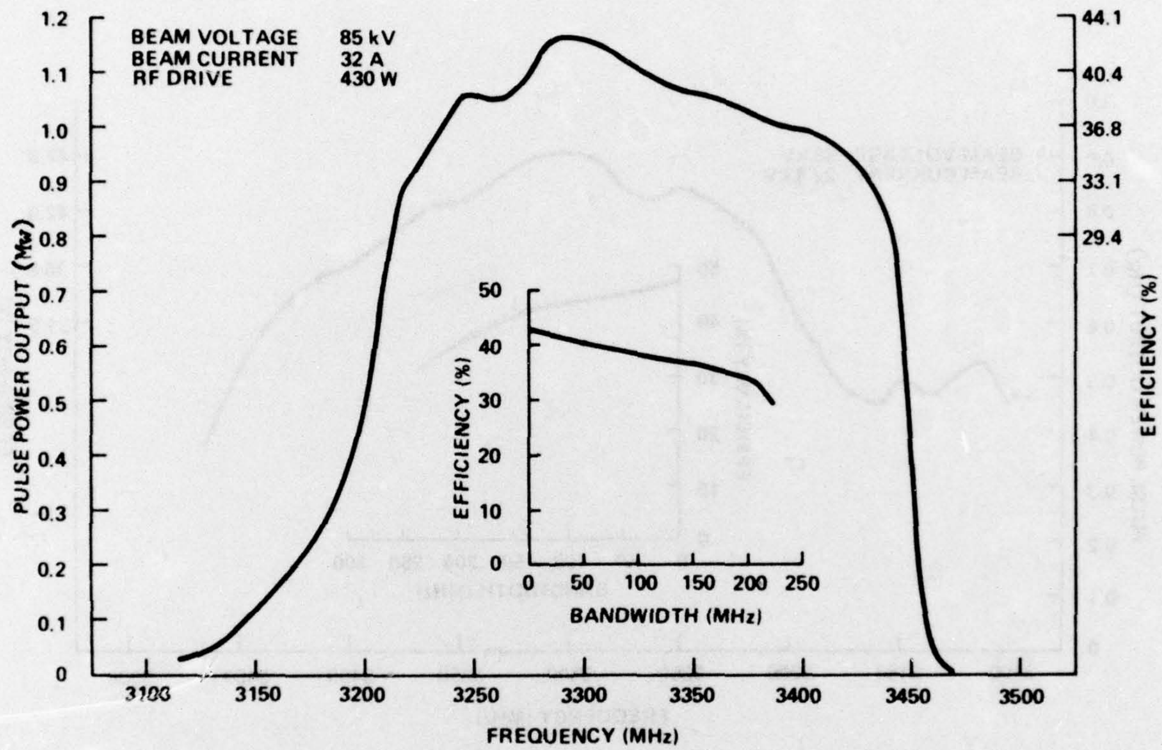

Figure 23. Constant Drive Power at 85 kV and 1.3 μperv

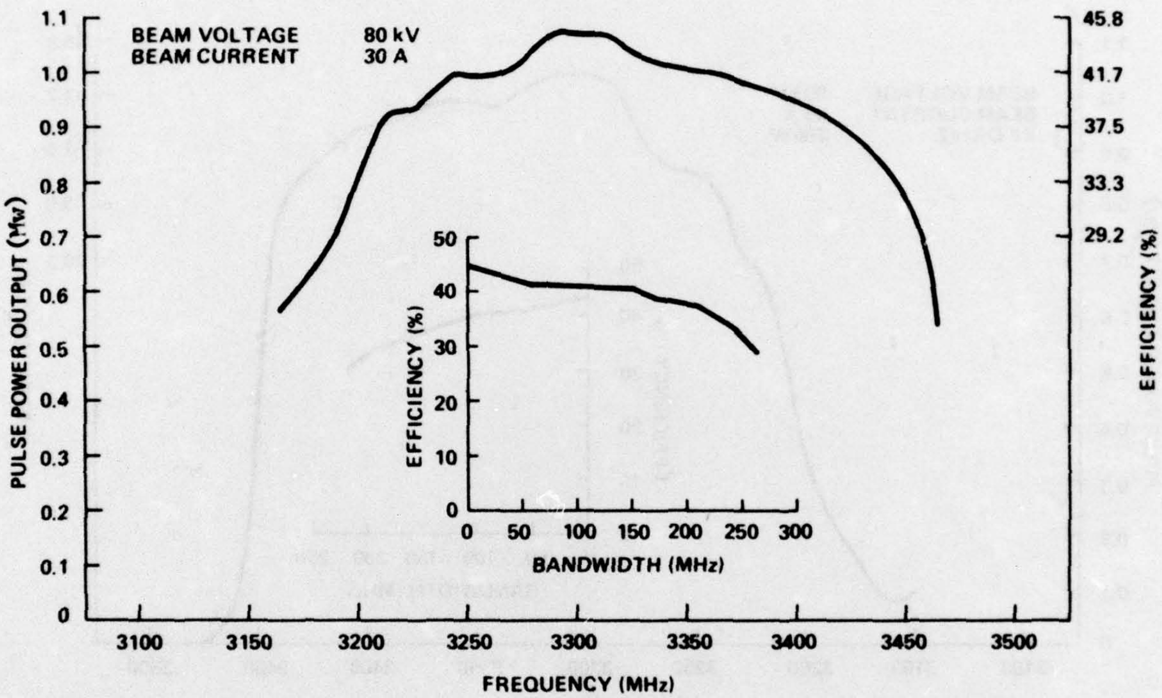

Figure 24. Saturated Power at 80 kV and 1.33 μperv

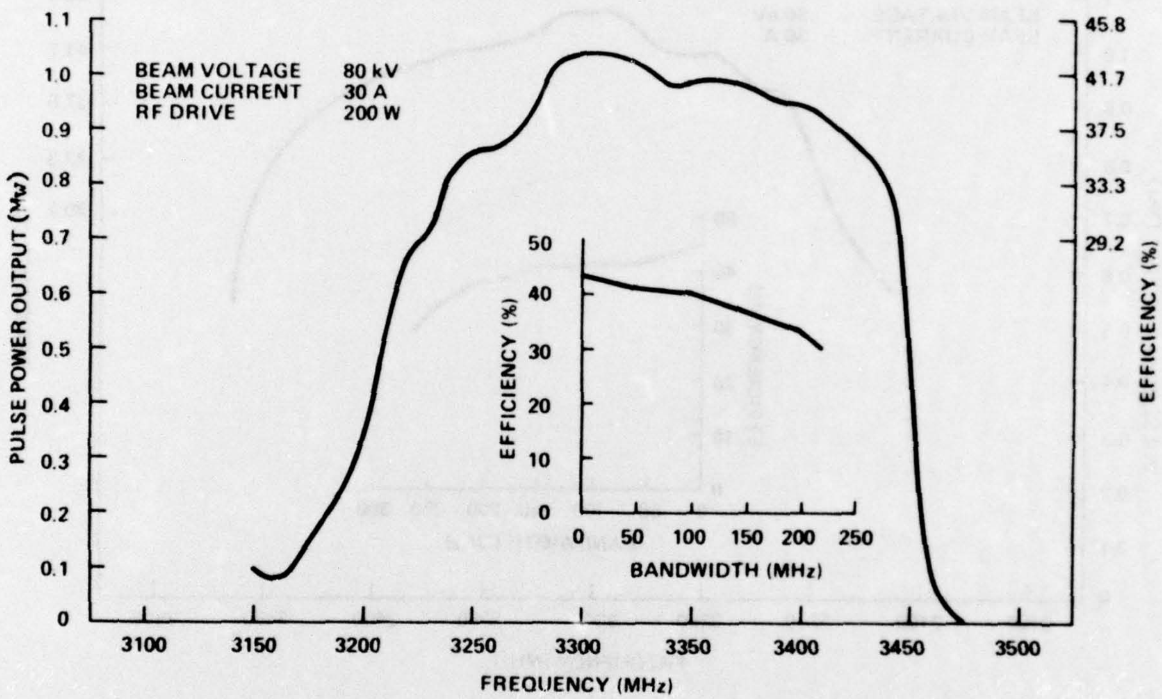

Figure 25. Constant Drive Power at 80 kV and 1.33 μperv

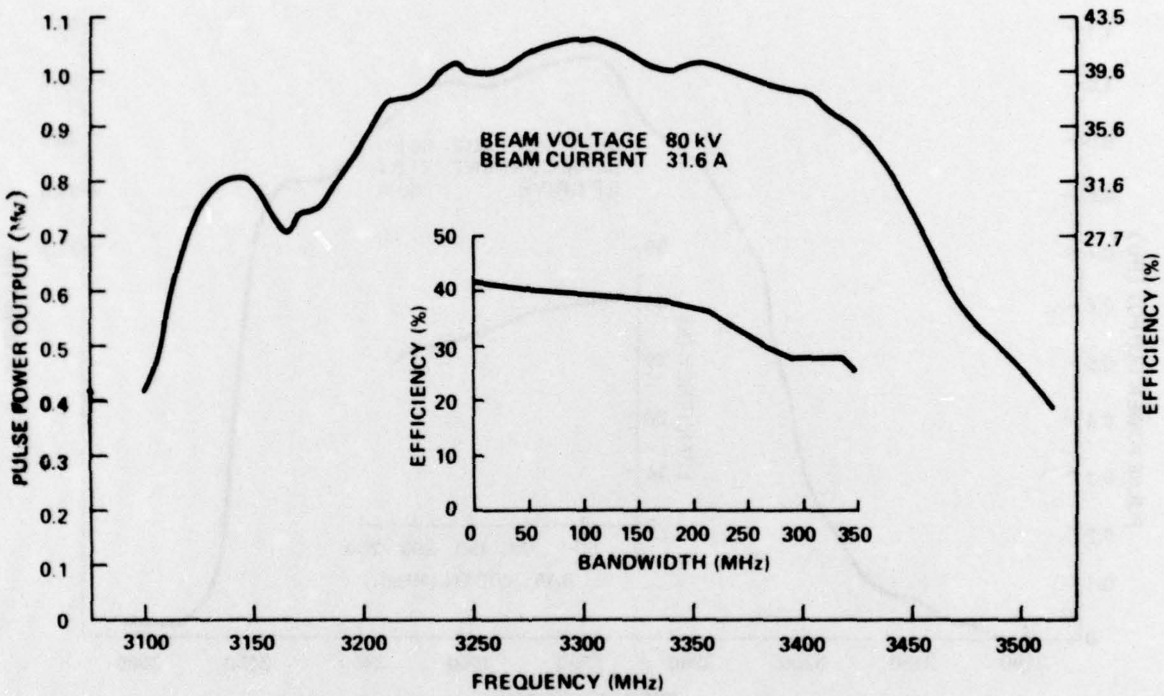

Figure 26. Saturated Power at 80 kV and 1.4 μperv

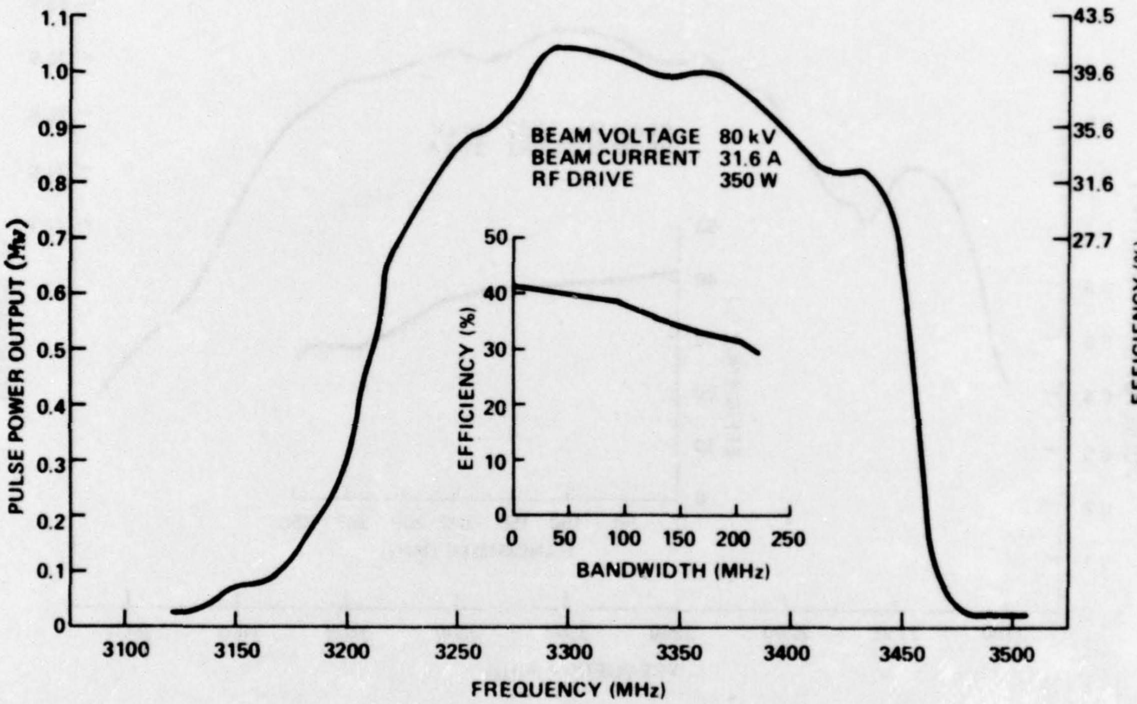

Figure 27. Constant Drive Power at 80 kV and 1.4 μperv

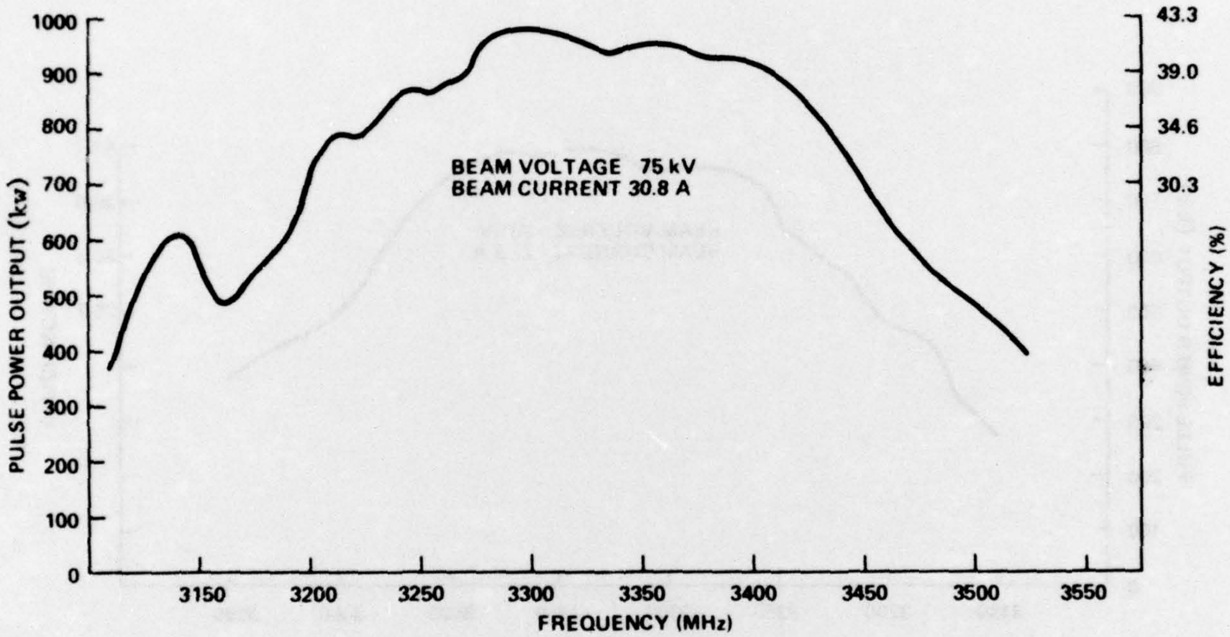

Figure 28. Saturated Power at 75 kV and 1.5 μperv

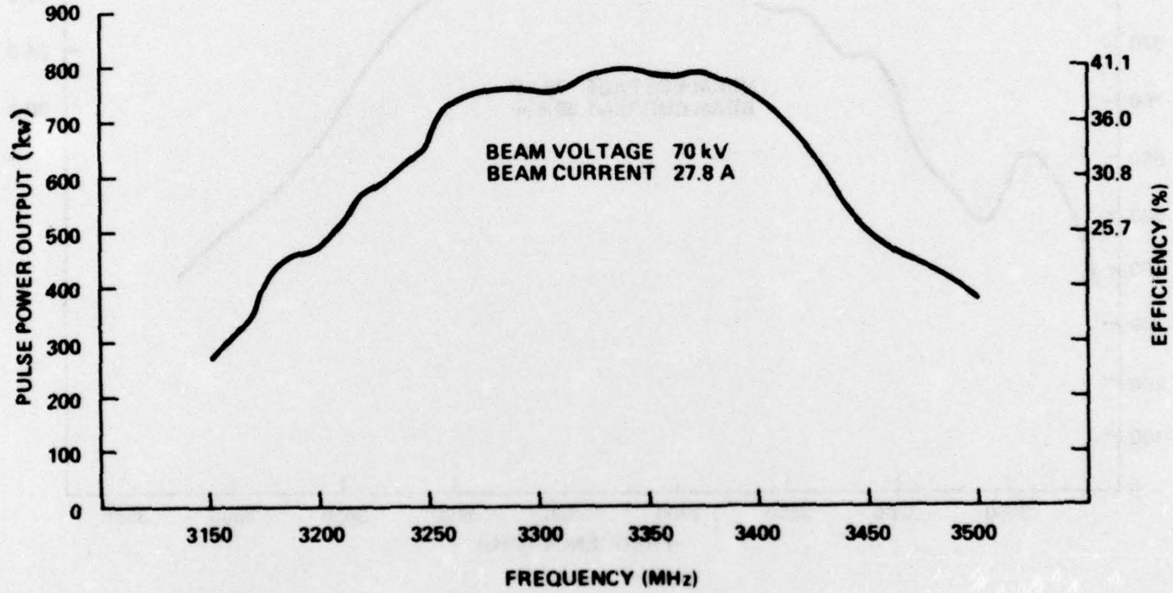

Figure 29. Saturated Power at 70 kV and 1.5 μperv

It is evident that further suppression of oscillatory tendencies and an increase in beam size will bring the efficiency from the measured 30-40-30 toward the computed 42-56-42. Just how far is not as evident; however, halfway might be a reasonable estimate. This would be 36% minimum efficiency over 330 MHz.

2. Broadband Gain

The broadband gain in the Phase II tube was limited to about 33 dB by the zero associated with cavity No. 3. This was determined by watching the small signal swept response and tuning cavity No. 3. The movement of both its associated pole and zero was immediately evident. The zero can be shifted above the band by increasing the external loading of the cavity.

3. Stability

Oscillations at the frequency of the π point of the main mode were detected at voltages below 40 kV at microperveances of 2.0 and higher. No π point oscillations could be detected at any voltage for microperveances below 2.0.

Oscillations at 6368 MHz and 5312 MHz were detected under rf drive conditions just below and at saturation. These are in the 5H mode and slot mode, respectively.

The Phase II tube has mode-loading cavities in three of its five full-height circuits. The addition of mode-loading cavities to a fourth full-height circuit should eliminate these drive-induced oscillations in a straightforward manner.

V. CONCLUSIONS

A. The Twystron designed and built on this program has demonstrated the practicality of 1 MW Twystrons by achieving the following performance levels:

1. 120 MHz bandwidth at 37.5% minimum efficiency and 38 dB gain.

2. 180 MHz bandwidth at 35% minimum efficiency and 37 dB gain.

3. 260 MHz bandwidth at 32% minimum efficiency at saturation.

4. 330 MHz bandwidth at 30% minimum efficiency at saturation.

B. Three secondary defects require correction.

1. An efficiency dip near the low end of the band.

2. RF drive-induced oscillations near saturation.

3. A gain hole in band.

C. The measured efficiencies given above are only 70% of the values expected. The major cause is deemed to be a beam diameter smaller than that used in the calculations and smaller than desired.

D. The evidence indicates that the 330 MHz bandedge efficiency can be increased above the 30% achieved on this program, but it is not clear if it can be increased to the 42% goal of the program.

VI. RECOMMENDATIONS FOR FUTURE EFFORT

The design built and tested on the program just completed requires four engineering modifications which will substantially improve its performance.

1. Reduce the amount of slot tapering.

2. Increase the external loading of the third cavity.

3. Add mode-loading cavities to full-height cloverleaf cavity No. 2.

4. Modify the gridded gun to provide a laminar beam with a 0.438 in diameter.

It is recommended that these modifications be implemented.

It is further recommended that, subsequent to the construction and test of a tube modified as described above, a detailed and complete analysis be made of any discrepancy between test performance and computer-predicted performance.